

# THE KEY COMPARISON FEASIBILITY EVALUATION BETWEEN LOW SHOCK AND HIGH SHOCK ACCELERATION CALIBRATION SYSTEM

*Jiun-Kai Chen<sup>1</sup>, Yu-Chung Huang<sup>1</sup>, and Hong-bo Hu<sup>2</sup>*

<sup>1</sup>Center for Measurement Standards ITRI, NML, Taiwan, [JoyHuang@itri.org.tw](mailto:JoyHuang@itri.org.tw)

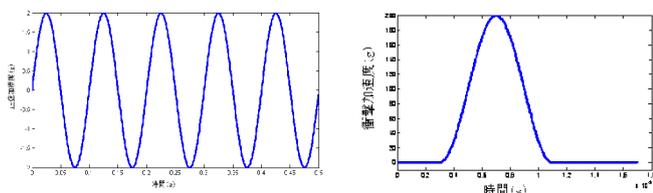
<sup>2</sup>Mechanics & Acoustics Division, NIM, China, [huhb@nim.ac.cn](mailto:huhb@nim.ac.cn)

**Abstract:** The article is mainly to study the feasibility for comparing calibration results by different shock excitation systems. It analyzes the difference and causes for the calibration results of the same accelerometer by the two different excitation systems. It provides technical references for comparison among related shock standards. With the development of social and economic globalization, such comparison will play a significant role in calibration ability, international recognition and elimination of technical barriers to trade.

**Keywords:** Shock calibration, shock exciter, comparison

## 1. INTRODUCTION

For national standards, participating in international bilateral or multilateral comparison can provide strong support to win internationally mutually recognized calibration and measurement capabilities (CMCs) for national measurement standards and assure the recognition for measurement capabilities by The International Bureau of Weights and Measures[1]. For calibration methods, ISO 16063 mainly specifies two mechanical vibration modes to calibrate accelerometer. They are sinusoidal vibration and shock vibration, respectively. Their typical vibration waveforms are shown in Figure 1. For the main difference between the two typical vibration modes, the sinusoidal vibration mode is for calibration at each discrete frequency point with small vibration amplitude ( common acceleration amplitude not over  $1000 \text{ m/s}^2$  ) ; while shock vibration mode is a transient shock pulse with short duration and large amplitude (acceleration amplitude up to  $100000 \text{ m/s}^2$  ) .



1.a Sinusoidal Vibration

1.b Shock Vibration

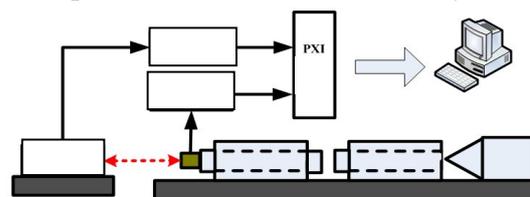
Figure 1 Two typical mechanical vibration modes

Mechanical vibration measurement methods are divided into primary method and secondary method. Primary method adopts laser interferometry to determine the input mechanical vibration acceleration accelerometer, so it has

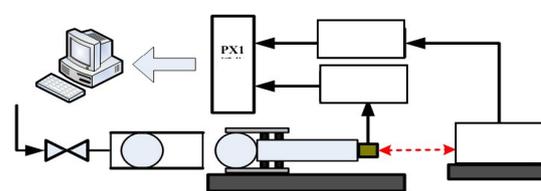
very high calibration precision. National Measurement Laboratory (NML), Taiwan has established shock vibration standards according to ISO 16063 specifications. The international standard ISO16063-13 for primary shock calibration was officially released in 2001[2]. Although the standard clearly specifies calibration equipment and method, there has been no comparison conducted internationally or regionally. Nevertheless, international experts in this field have started researches[3,4]. The background for this research is to conduct preliminary research on shock comparison among related economies under Asia/Pacific Metrology Program. The main content of this article is to analyze the principles and typical shock waveforms with focus on two ISO16063-13 specified typical shock wave systems, and compare calibration results for the same accelerometer, and analyze the differences and causes, and propose feasible assessment for shock comparison.

## 2. ANALYSIS ON TWO TYPICAL SHOCK EXCITATION SOURCE SYSTEMS

### 2.1 Principles of Shock Excitation Source System



2.a Shock Calibration System based on Rigid Body Motion

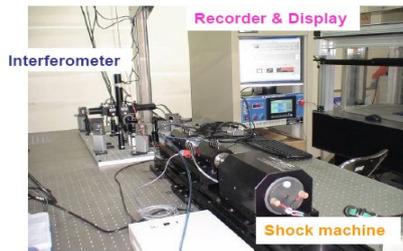


2.b Shock Calibration System based on Hopkinson Bar

Figure 2 Structural Diagrams for Two Typical Shock Calibration Systems

In ISO16063-13, the primary shock calibration standard specifies two typical shock source systems: the first is based on rigid body motion, mainly using mechanical collision between impact hammer and anvil to generate shock

acceleration with half-sine acceleration waveform as time domain waveform ; the second shock source system is based on Hopkinson bar, mainly utilizing the passing of stress wave generated from collision in a slender bar and the reflection at the free end to generate a shock source with sinusoidal waveform as shock acceleration time domain waveform. The structural diagrams and pictures for the two shock source systems are shown in Figure 2 and Figure 3. According to the specifications in the standard, in general, the shock excitation source based on rigid body collision generates shock acceleration peak range from 100 m/s<sup>2</sup> to 5000 m/s<sup>2</sup> and shock pulse duration less than 10 ms; while the shock excitation source based on Hopkinson bar generates shock acceleration that can exceed 10<sup>5</sup> m/s<sup>2</sup> and shock pulse duration generally around 0.1 ms.



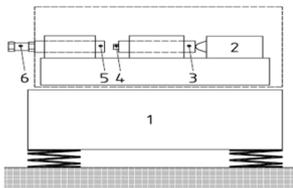
3.a Rigid Body Collision Shock System Established by ITRI/ Center for Measurement Standards



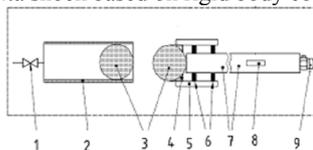
3.b Hopkinson Bar Shock System by National Institute of Metrology China

Figure 3 Actual Pictures for Two Typical Shock Calibration Systems

The calibration systems for the above two shock sources adopt laser interferometry for measurement. Their data computing process follows the algorithm specified by ISO16063-13 for shock acceleration signal. The excitation structure and principle for the two devices is shown in Figure 4.



1. isolation mass block 2. excitation component  
3.hammerhead 4. rubber pad 5. anvil 6. accelerometer



1. gas valve 2. air pipe 3. steel ball 4. rubber  
5. aluminum tube 6. retaining ring 7. Hopkinson bar  
8. strain gauge 9. accelerometer

4.b shock excitation source based on Hopkinson bar

Figure 4 System Configuration Diagrams for Two Typical Shock Excitation Sources

The mechanical system in Figure 4.a is an excitation system based on rigid body motion. Its operating principle is based on the collision between two completely same rigid bodies that leads to obvious displacement and generated shock acceleration. Its waveform approximates the half-sine shock acceleration waveform. The collision process for the mechanical excitation system is as follows: the excitation unit impacts the hammer with a certain level of energy; the hammer accelerates freely and impacts an anvil with accelerometer at the other end; the anvil accelerates to apply shock acceleration onto the accelerometer.

The following things should be noted for the above shock excitation source. 1. Moving Unit : The moving unit for the excitation system mainly consists of two components, anvil and hammer. To assure good shock waveform, the standard specification suggests the dimensions for the two components are 200 mm in length and 30 mm in diameter. For the materials to be processed, increasing natural resonance frequency is generally the main consideration. The natural frequency for anvil and hammer must be larger than  $10/T$  with  $T$  a shock pulse width time. 2. Installation and Support for Moving Unit : The principle for the mechanical shock excitation source to generate shock acceleration waveform is based on rigid body collision. To assure a good shock acceleration waveform, it is necessary for the two moving components to be centered and freely collide with each other. The standard specifies that the deviation of the central lines for both components should be within  $\pm 0.2$  mm. To minimize the effect of other parts of the mechanical structure on the moving unit, such as external friction, resonance from other parts of the mechanical structure and friction reduction etc., the support for moving unit adopts air bearing, which can reduce friction and provide isolation from other parts. 3. Vibration Isolation for the Whole System : The whole mechanical shock system must be installed on a vibration isolation block of large mass to prevent from relative motion due to ground influence and any effect on calibration process due to the support structure of mechanical excitation part.

The mechanical excitation system in Figure 4.b is based on Hopkinson bar. Its main components include a moving steel ball and a slender bar, i.e. Hopkinson bar. The operating principle for the mechanical excitation system is based on that stress wave passes through the slender bar and gets reflected at the free end, generating shock acceleration. The operating process is as follows: the steel ball subject to high-pressure gas accelerates to impact one end of the supporting Hopkinson; the stress due to collision passes along the slender bar to the other end and gets reflected from the free end where an accelerometer is installed; therefore, high shock acceleration is generated.

For such type of shock generation, the following things must be satisfied to meet the requirements for uncertainty specified by the standard : 1. Hopkinson Bar Size : The length to diameter ratio must be larger than 10. Thus, the stress wave due to lateral effect will decay to the minimum.

2. Hopkinson Bar Support : Hopkinson bar must be installed with flexibility and firm support. Resonance effect from other parts of the excitation system should be prevented, i.e. it is better to separate the bar from the support system or adopt vibration isolation, such as air bearing or vibration isolation rubber support. 3. It must be assured that the installation end of the accelerometer has the minimum lateral motion during the collision process and therefore the centerlines of the steel ball and the bar must be on the same horizontal line. 4. System Vibration Isolation Treatment : As described previously, the whole system must be installed on a vibration isolation block of large mass to reduce the effect of ground and environment on the excitation system.

### 2.2 Typical Shock Acceleration Waveform

For the shock source system based on rigid body collision, the shock acceleration waveform is a half-sine-squared shock, as shown in Equation ( 1 ) .

$$a_{\sin}(t) = a_{\sin,\max} \sin^2\left(\pi \frac{t}{T_{\sin}}\right) \quad 0 \leq t \leq T_{\sin} \quad (1)$$

In the above equation,  $T_{\sin}$  is the duration for shock pulse width and  $a_{\sin,\max}$  is shock acceleration peak value. By integrating Equation ( 1 ) , we can obtain the expression corresponding to the velocity waveform as in Eq. ( 2 ) .

$$v_{\sin}(t) = a_{\sin,\max} \left[ \frac{t}{2} - \frac{T_{\sin}}{4\pi} \sin\left(2\pi \frac{t}{T_{\sin}}\right) \right] \quad (2)$$

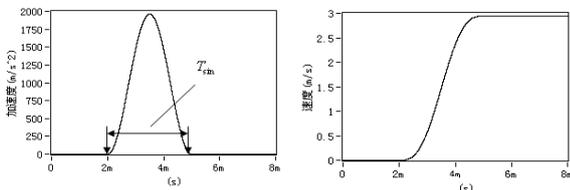
For shock source system based on Hopkinson bar, the principle for the shock system can use a Gaussian function to express the generated shock velocity waveform as in Equation ( 3 ) .

$$v_G(t) = v_{G,\max} e^{-\frac{1}{2}\left(\frac{t-t_0}{T_G}\right)^2} \quad 0 \leq t \leq T_d \quad (3)$$

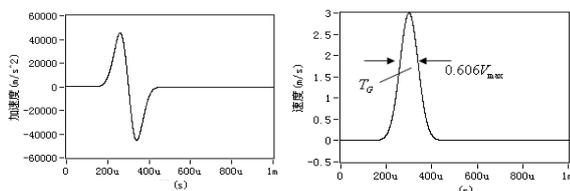
In the above equation,  $T_G$  is the shock pulse width corresponding to the Gaussian velocity waveform. By differentiating Equation ( 3 ) , we can obtain the generated shock acceleration waveform as shown in Equation ( 4 ) .

$$a_G(t) = -\frac{v_{G,\max}}{T_G^2} (t-t_0) e^{-\frac{1}{2}\left(\frac{t-t_0}{T_G}\right)^2} \quad (4)$$

For the above two typical shock excitation systems, they generate the typical waveform as shown in Figure 5.



5.a Waveforms of Acceleration and Velocity Generated by Collision Type System



5.b Waveforms of Acceleration and Velocity Generated by Hopkinson Bar Shock System  
Figure 5 Shock Waveforms Generated by Two Typical Shock Source Systems

### 3. COMPARISON OF CALIBRATION RESULTS FROM TWO TYPICAL SHOCK EXCITATION SOURCE SYSTEMS

The internationally recognized standard accelerometer Endevco 2270/133 was selected and calibrated on the above mentioned two shock calibration systems. The nominal charge sensitivity for the accelerometer was 0.22 pC/(m/s<sup>2</sup>). The rated shock acceleration was >150,000 m/s<sup>2</sup>. For the two shock calibration systems, one was a shock source system established by the Center for Measurement Standards, ITRI, based on rigid body collision, with generated shock acceleration range 2×10<sup>2</sup> to 1×10<sup>4</sup> m/s<sup>2</sup> and shock pulse width 1 to 5 ms[5] ; while the other was a shock source system established by National Institute of Metrology, China, based on Hopkinson bar, with shock acceleration range 5×10<sup>3</sup> to 1×10<sup>5</sup> m/s<sup>2</sup> and shock pulse width 50 to 150 μs. The two typical shock source systems basically comprise the shock acceleration standard devices established by each laboratory in compliance with ISO16063-13 standards. Within the technical capability for each device, an accelerometer was selected and calibrated to obtain the results as shown in Figure 6.

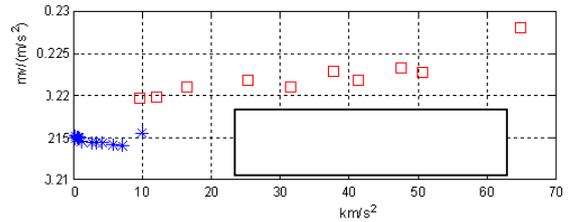


Figure 6 Comparison of Calibration Results from Two Typical Shock Source Systems

It can be found from Figure 6 that the difference between the calibration results from the two shock source systems is large with relative deviation over 8 %. The relatively small measurement uncertainty and the relatively large measurement tolerance make the meaning of the comparison questionable. Therefore, direct comparison cannot be made between the calibration results from different shock source systems.

### 4. ANALYSIS ON REASONS FOR BEING UNABLE TO MAKE DIRECT COMPARISON

The self-measurement system for accelerometer under generally ideal conditions can be considered as a linear time-invariant dynamic system. Within the linear dynamic range, it is equivalent to a single degree of freedom spring mass system and can be expressed by the following second order system [6].

$$H(s) = \frac{S_0 \omega_0}{s^2 + 2\delta \omega_0 s + \omega_0^2} \quad (5)$$

In Eq. (5), parameter  $S_0$  is the static gain for accelerometer;  $\omega_0 = 2\pi f_0$  is resonant frequency;  $\delta$  is accelerometer damping ratio. For details in accelerometer structure and its modeling theory, please refer to the literatures [7,8,9]. According to general characteristic data for accelerometer calibration, accelerometer is assumed to have static amplification factor  $S_0 = 2.0 pC/g$ , resonance frequency  $f_0 = 35$  kHz, and then resonance angular frequency is  $\omega_0 = 219911 \text{ rad/s}$  and damping coefficient is 0.01. When the above parameters are entered in Equation (5), the frequency response of transfer function for the accelerometer can be obtained as shown in Figure 7.

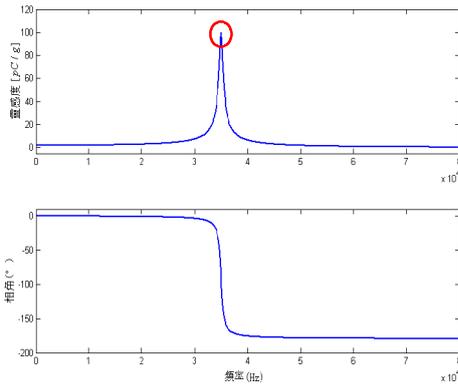


Figure 7 Frequency Response for Accelerometer

Since the frequency for accelerometer calibration is usually set from 0 to 20 kHz, the dynamic response for the model from 0 to 20 kHz is shown in Figure 8.

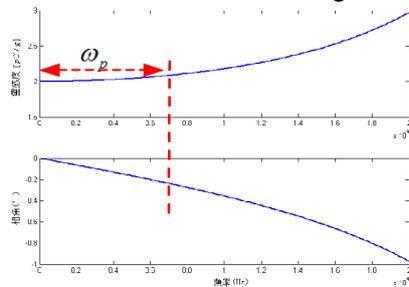


Figure 8 Response for Accelerometer Frequency from 0 Hz to 20 kHz

According to the definition of working bandwidth in the reference [6], it can be found that the amplitude frequency response is almost a constant ( $< 1\%$ ) within the working bandwidth  $\omega_p$  of accelerometer. Besides, the phase frequency response also has very good linearity. When the measured frequency does not exceed  $\omega_p$ , the output distortion is very small and the measurement is accurate; while the frequency component of the measured signal exceeds the working frequency, the output waveform will have significant distortion. Figure 9 shows the waveform frequency for the shock acceleration generated by the two typical shock vibration systems and the frequency response curve for the accelerometer.

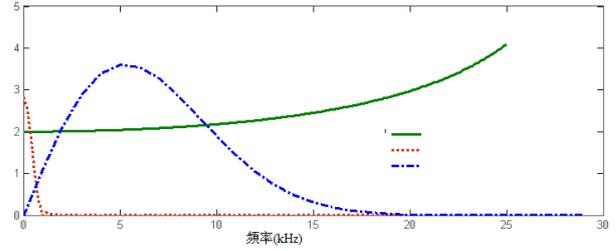


Figure 9 Frequency Response for Accelerometer and Frequency Response for the Shock Waveform Generated by the Two Shock Systems

It can be found from Figure 9 that the frequency response for collision type shock system is in lower frequency ( $< 3$  kHz), while the frequency response for Hopkinson bar type shock system is distributed in higher frequency ( $< 20$  kHz). The frequency response characteristic of accelerometer and the difference in the frequency component of the shock waveform generated by the two excitation systems cause different results. However because collision type excitation system generates wider time domain waveform pulse width, accelerometer characteristic is within working bandwidth, the difference in results is relatively small.

## 5. ASSESSMENT ON COMPARISON METHOD

### 5.1 Direct Comparison in Shock Sensitivity

From the previous description, it can be found that the results for laser primary calibration of accelerometer by different shock source systems cannot necessarily be compared. The result in shock sensitivity obtained from shock calibration is related to shock waveform. According to the characteristics of shock excitation system and accelerometer, the following methods can be used for shock comparison.

By definition, shock sensitivity is the ratio of the peak value of output voltage waveform to the peak value of input acceleration waveform for accelerometer, i.e.

$$S_{sh} = u_{peak} / a_{peak}$$
, which  $u_{peak}$  is peak value of output voltage for accelerometer, while  $a_{peak}$  is the peak value of input acceleration accelerometer. Due to non-ideal frequency response characteristics for accelerometer, the calculated shock sensitivity is related to the shock waveform and shock waveform pulse width. The parameter in direct comparison is shock sensitivity. The major technical standard for the comparison is current ISO16063-13. The comparison is under the conditions that are strictly specified time domain shock pulse width and waveform for the shock source. Thus, the comparison can assure the frequency component of shock waveform from different systems is consistent or within working frequency range. Therefore, the comparison for the same shock system is feasible, for example, collision type shock source system.

### 5.2 Amplitude Spectrum for Complex Sensitivity

It can be found from the definition of complex sensitivity of accelerometer that complex sensitivity

$\hat{S} = S(f_n)$  is a function of frequency and the only determined value. So primary method for shock calibration can be considered to obtain the complex sensitivity for the accelerometer at each frequency point and further to compare its amplitude spectrum and even phase spectrum. Such type is similar to the comparison based on sinusoidal vibration. The comparison requirements are to select suitable frequency range and assure that the frequency component for the acceleration waveform generated by different shock source systems is covered within the range. The major technical standard for the comparison is current ISO16063-13. Thus, a comparison is made on the selected complex sensitivity spectrum of the accelerometer from the above mentioned two typical shock source systems. Table 1 shows the sensitivity at each frequency point for the calibration of accelerometer by collision type shock system. Table 2 shows the sensitivity at each frequency point for the calibration of accelerometer by Hopkinson bar shock system. The comparison of Table 1 and Table 2 is plotted in Figure 10. It can be found from the figure that at the same frequency (< 3 kHz) the calibration results from two different shock source systems can be compared.

Table 1 Sensitivity at Each Frequency (Collision Shock)

Frequency (Hz)	200	400	600	800	1000	1200	1400
Sensitivity (pC/m s <sup>-2</sup> )	0.2150	0.2148	0.2151	0.2151	0.2153	0.2151	0.2149
Frequency (kHz)	1.6	1.8	2	2.2	2.4	2.6	2.8
Sensitivity (pC/m s <sup>-2</sup> )	0.2149	0.2149	0.2154	0.2156	0.2151	0.2149	0.2153

Table 2 Sensitivity at Each Frequency (Hopkinson Bar)

Frequency (kHz)	1	2	3	4	5	6	7	8
Sensitivity (pC/m s <sup>-2</sup> )	0.2151	0.2164	0.2141	0.2167	0.2156	0.2222	0.2233	0.2337

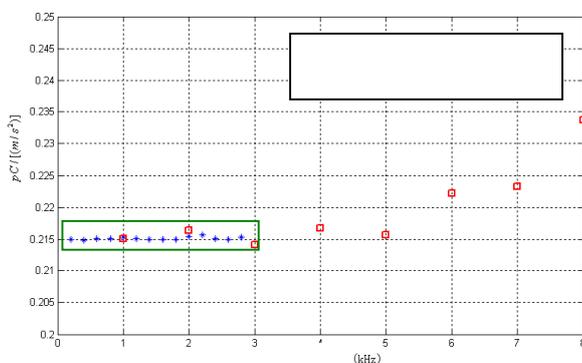


Figure 10 Comparison of Complex Sensitivity for Accelerometer Calibration by Two Different Typical Shock Source Systems

## 6. CONCLUSIONS

The article is mainly to study the feasibility for comparing calibration results by different shock excitation systems. It includes description of the principle of the two typical shock excitation systems specified in ISO16063-13 standard and typical shock acceleration waveform. It also analyzes the difference and causes for the calibration results of the same accelerometer by the two different excitation systems. On this basis, the study further assesses the comparable methods for primary calibration method for accelerometer by different shock excitation systems. This

work provides technical references for comparison among related shock standards. With the development of social and economic globalization, such comparison will play a significant role in calibration ability, international recognition and elimination of technical barriers to trade. As shock calibration is underway, it provides strong support to international recognition for the CMC capability of such shock standard device.

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